SuperP2G

Synergies Utilising renewable Power REgionally by means of Power To Gas

Model-based operation and planning for PtH2 – Knowledge and experience developed based on University-Industry research collaboration in Denmark

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Acknowledgement: GreenLabSkive,
Yi Zheng (DTU)

Smart Energy Systems ERA-Net

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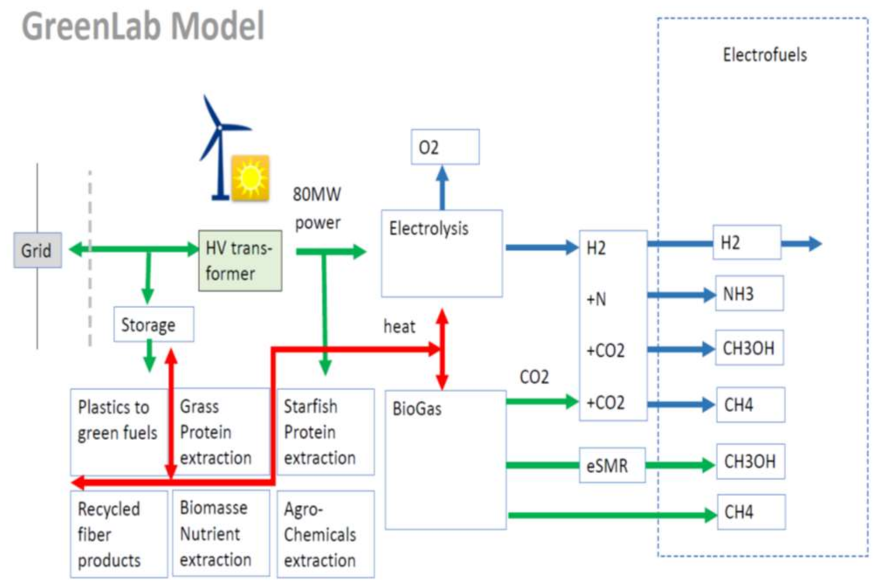
WP2 Denmark Case "Skive" Overview

has the objective to…

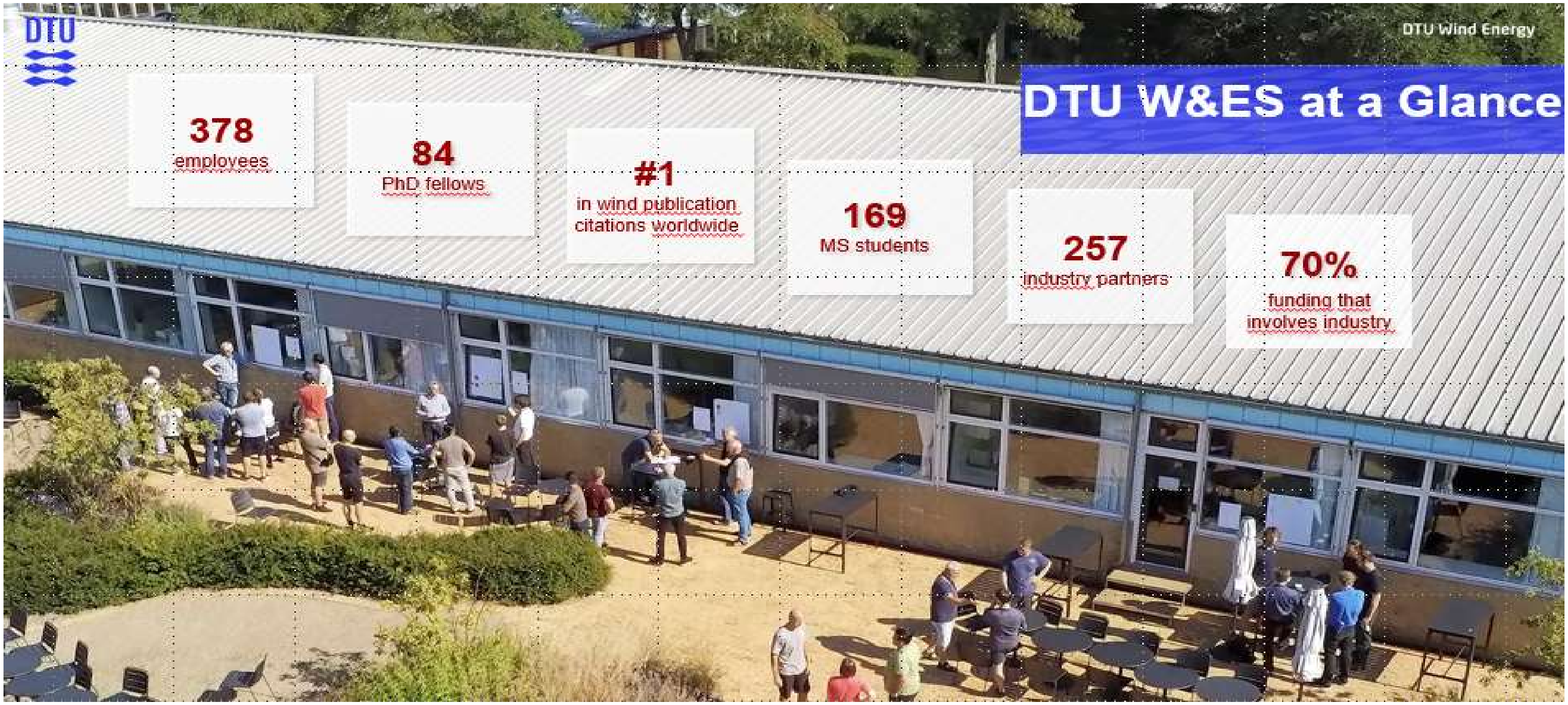
make it possible for **local multi-energy carrier-based business park** to manage **multiple value streams** in **real time** as well as **optimise the infrastructure set-up** in a feasible way.

The goal is to…

- develop **applicable solutions** to this end
- and **transfer the knowledge** to the involved Need-Owner

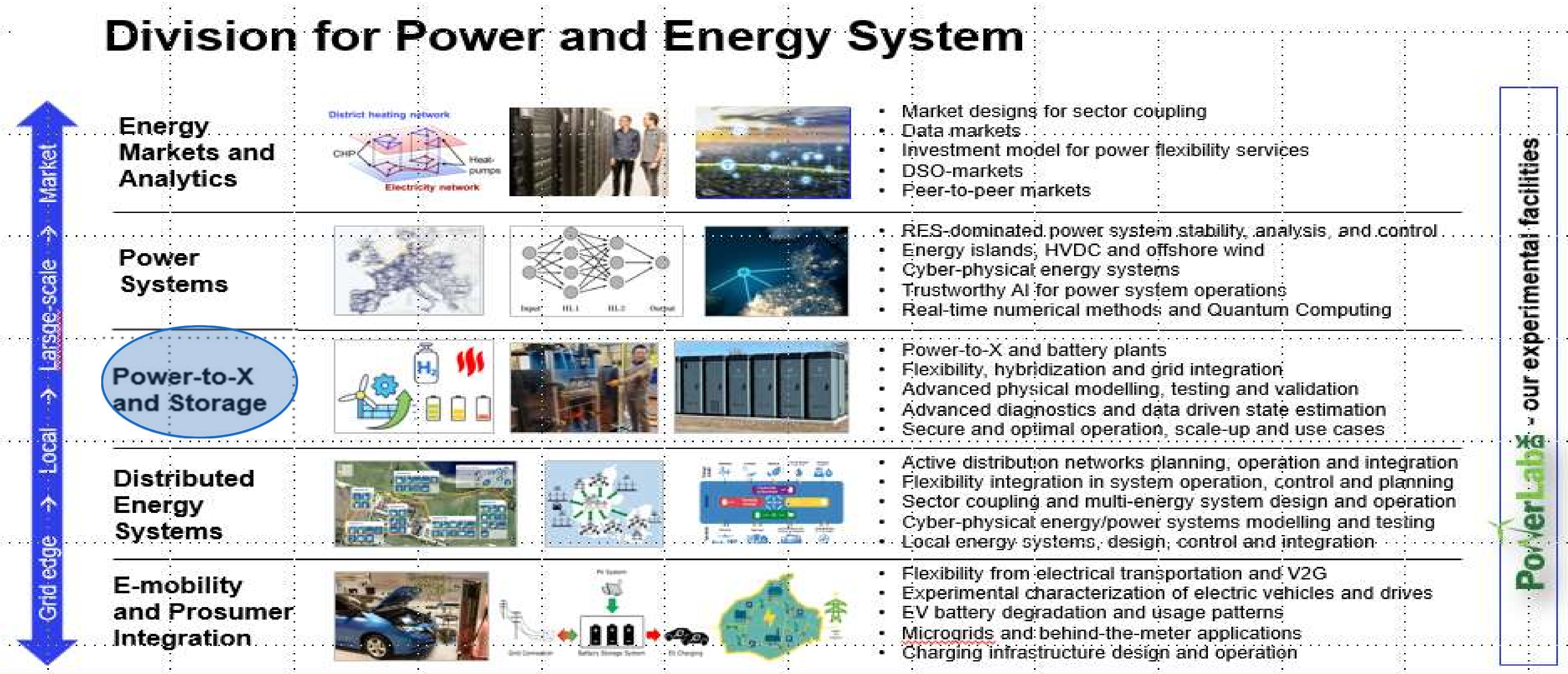


PTX section at DTU Wind and Energy Systems



https://wind.dtu.dk/about

PTX section at DTU Wind and Energy Systems



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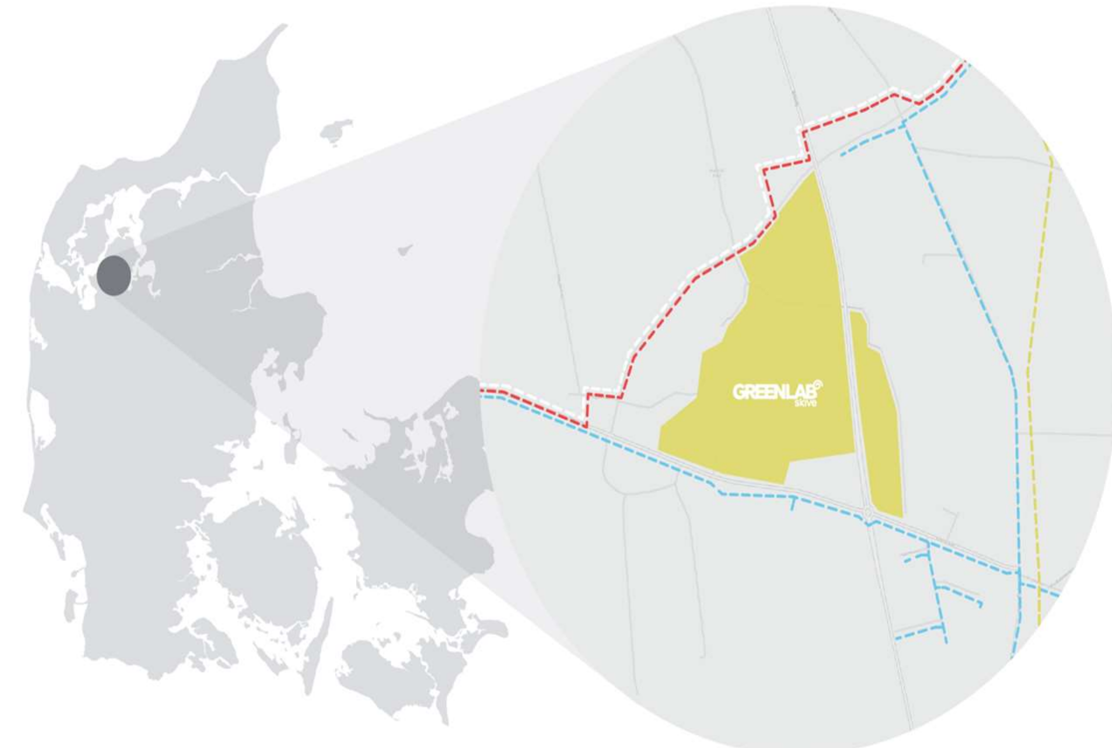
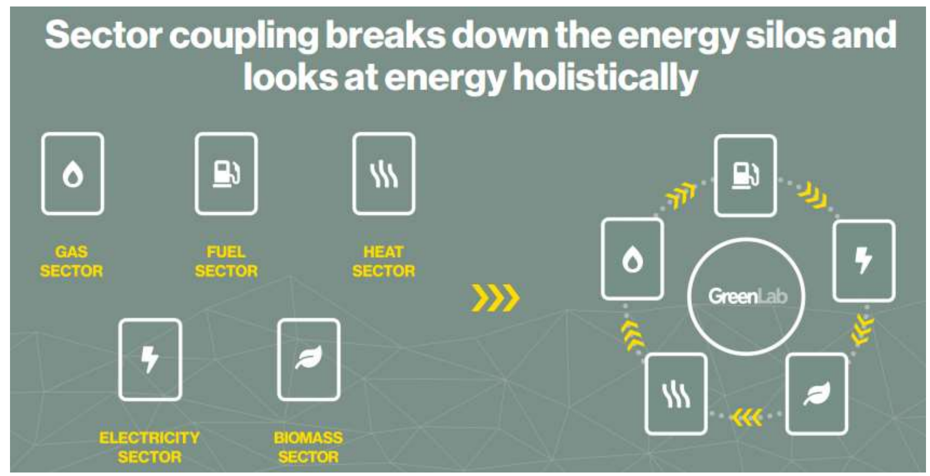
GreenLab Skive A/S



District heating pipeline

Gas distribution pipeline (4bar)

Gas distribution pipeline (40bar)



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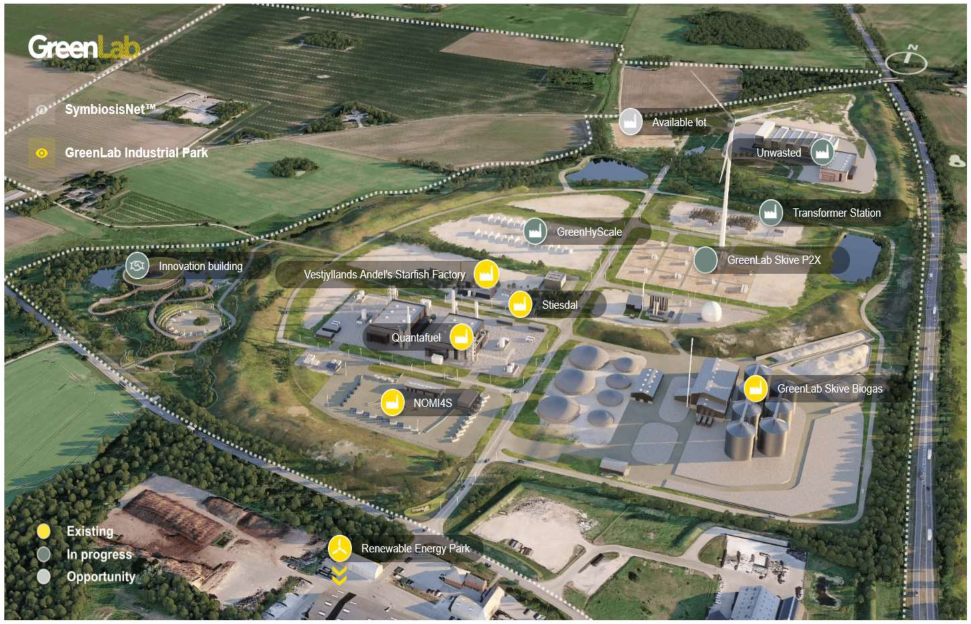
GreenLab Skive A/S

2019 - Blueprint

2023 - Partially Operational



WP2 Denmark Case "Skive"
Model-based operation and planning for **PtH_2**

1 Advanced electrolysis models

- Thermal-electric properties
- Electrochemical properties
- Dynamic startup/shutdown
- Multi-states transitions
- MILP optimization integration

4 PtH_2 system optimal investment planning

- Optimal sizing
- Multi-objective optimization
- Risk aversion

2 PtH_2 system optimal operation

- Feasible region of electrolysers
- Various uncertainties
- Short term forecast
- Grid ancillary service, peak shaving and frequency regulation
- Spinning reserve

3 Marke and regulatory constraints

- Spot and balancing market
- Ancillary market
- Renewable quotas
- Carbon credits

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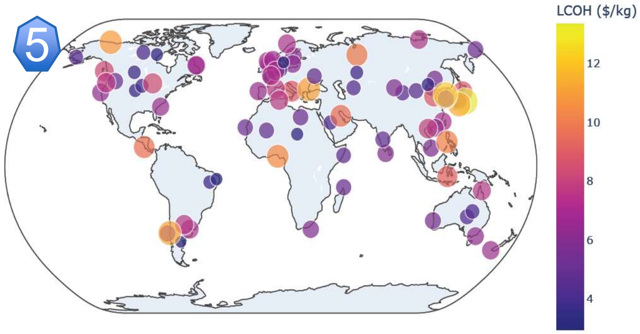
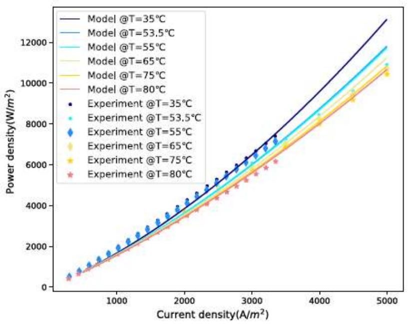


1. First principle-based **electrolysis dynamic model** involving operation states and thermo-electric properties
2. Risk-averse stochastic **optimal operation strategies** in view of uncertainties, incl. renewables, markets, PtX configurations
3. Techno-economic analysis of using electrolyser for **multiple grid services**
4. Co-optimization of **investment and operation decision**
5. Model **fidelity** has impacts on results

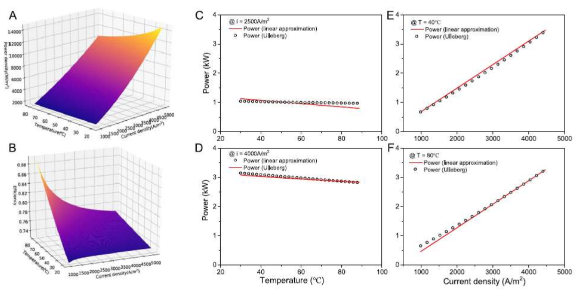
Low-temperature electrolysis dynamic models

Key output 1: electrolysis dynamic model involving operation states and thermo-electric properties

Nonlinear input/output properties



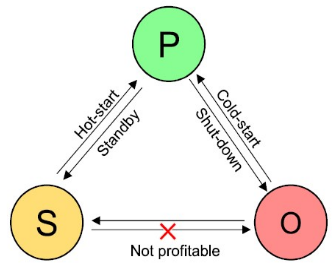
Power as a nonlinear function of current



Power as a nonlinear function of current and temperature

Reveal the relations among power, current and temperature

State transitions



Production, standby and off states

$$A p_t^b \underline{i} \le I_t \le A p_t^b \bar{i} \quad \forall t \ge 0$$

$$s_t^b p_s \le p_t \le p_t^b p_p + s_t^b p_s \quad \forall t \ge 0$$

$$p_s = \frac{\frac{1}{R_t}(T_s - T_a)}{n_c} \quad \forall t \ge 0$$

$$0 \le \dot{Q}_{\mathrm{cool},t} \le p_t^b M \quad \forall t \ge 0$$

$$p_t^b + s_t^b + i_t^b = 1 \quad \forall t \ge 0$$

$$p_t = aT_t + bI_t + c + \delta_{1t} + \delta_{2t} \quad \forall t \ge 0$$

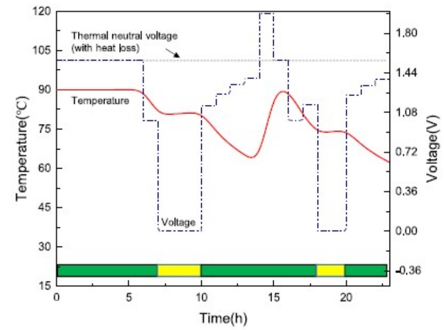
$$-M s_t^b \le \delta_{1t} \le M s_t^b \quad \forall t \ge 0$$

$$-M i_t^b \le \delta_{2t} \le M i_t^b \quad \forall t \ge 0$$

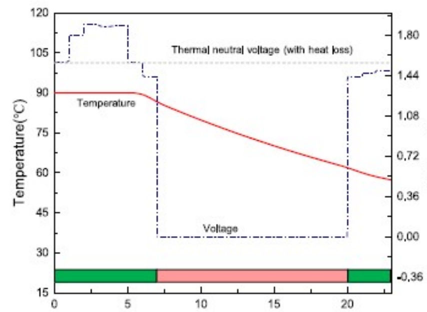
$$s_t^b + i_{t-1}^b \le 1 \quad \forall t \ge 1$$

MILP representative state transition equations

Temperature dynamic characterization



Temperature variation in standby states



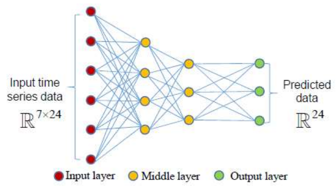
Tempearture variation during off states

Short-term optimal operation of PtH systems

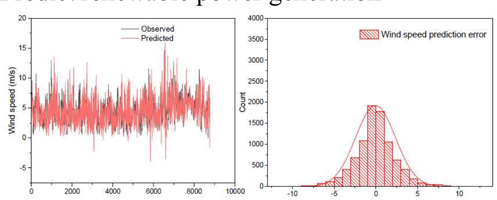
Key output 2: Optimal operation in view of uncertainties from renewables and power markets

Short-term forecast

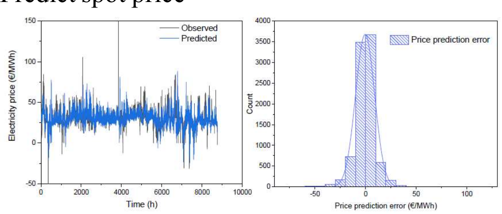
Forecast based on neural networks



Predict renewable power generation



Predict spot price

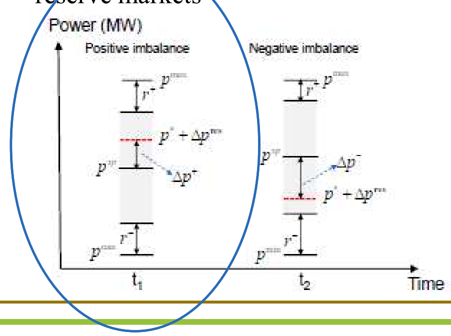


Technical feasibility and market constraints

Technical constraints

- **Feasible region of electrolysis**
- **Hydrogen storage**
- **Battery constraints**
- **Electric components**

Constraints from spot, balancing and reserve markets



Uncertainties

- **Forecast errors**
- **Parameter perturbation**

↓

- **Stocastic optimization based on scenarios**
- **Risk-averse stochastic optimization**
- **Robust optimization**
- **Chance-constrained robust optimization**

↓

Improve the expected revenues and reduce risks

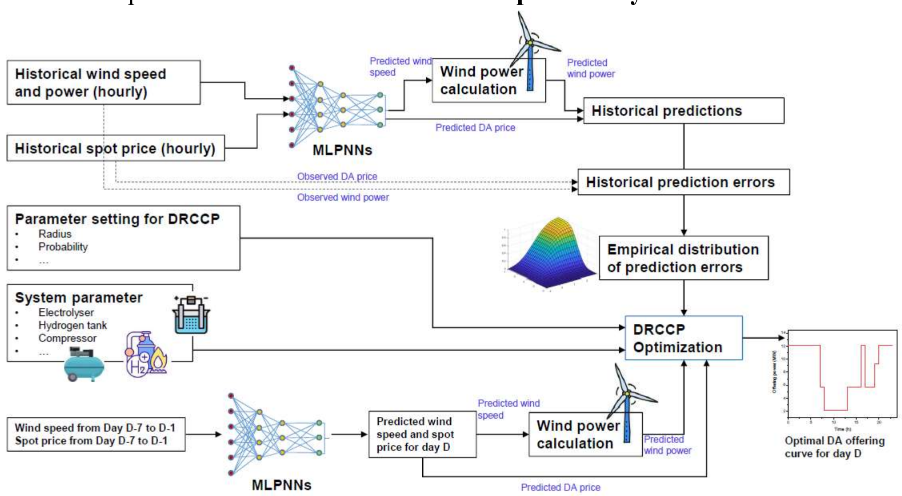
Data-driven robust optimization on system operation

Key output 2: Stochastic optimization depends on assumed distribution; robust optimization is too conservative

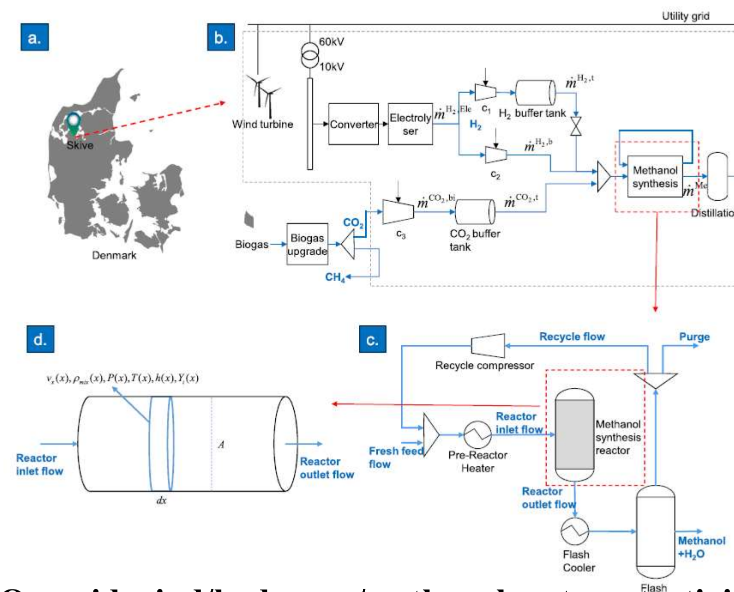
Data-driven robust chance-constrained optimization based on Wasserstein metrics

$$W(\mathbb{P}_1, \mathbb{P}_2) = \inf \left\{ \int_{\Xi \times \Xi} \|\xi_1 - \xi_2\| \mathbb{Q}(d\xi_1, d\xi_2) : \begin{array}{l} \mathbb{Q} \text{ is a joint distribution of } \widehat{\xi}_1 \text{ and } \widehat{\xi}_2 \\ \text{with marginals } \mathbb{P}_1 \text{ and } \mathbb{P}_2, \text{ respectively} \end{array} \right\}$$

This metric quantifies the **distance between two probability distribution**



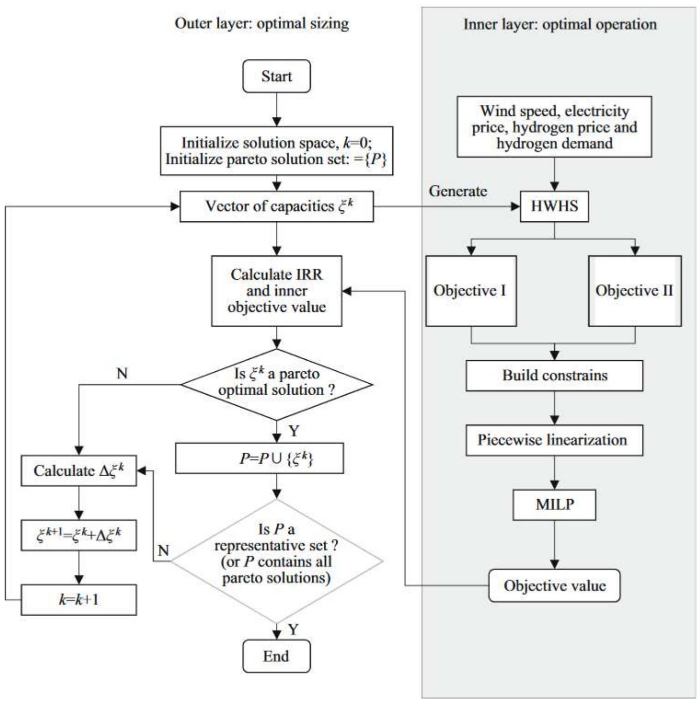
On-grid wind/hydrogen system participating in spot market

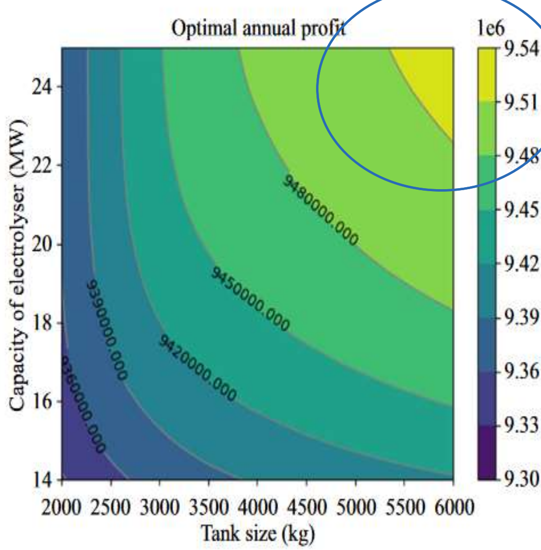


On-grid wind/hydrogen/methanol system stratigically participates in spot market

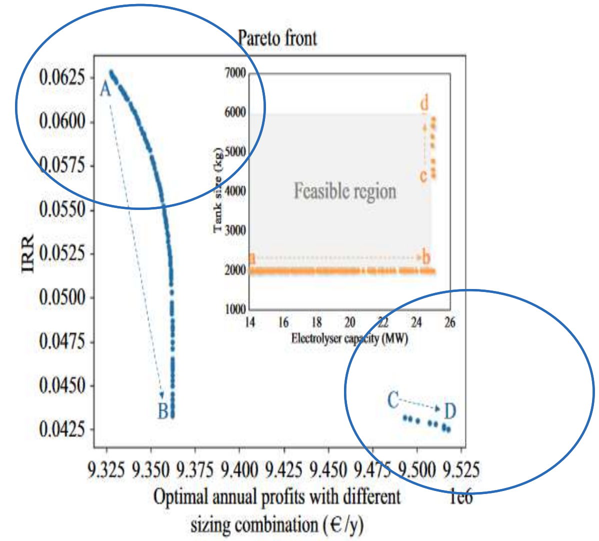
Optimal planning in view of optimal operation

Key output 3: An optimal investment planning framework that incoperates optimal operation





Influence of system sizing on operational optimal profit.



Pareto front of the multi-objective optimization coping with the trade-off between system investment payback (IRR) and optimal operationa profits.

PtH system providing frequency regulation reserves

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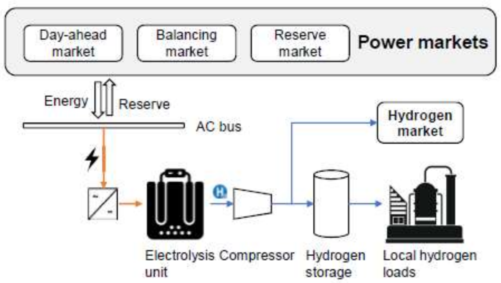
Key output 4: Economic analysis of using electrolyser for multiple grid services

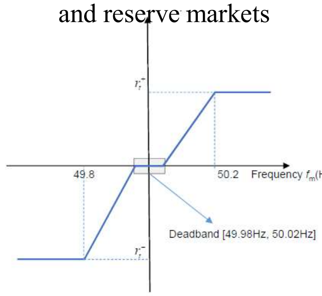
Electrolysis system:

Second-level dynamic response; can provide **FCR，aFRR，mFRR services**

Participation in multiple markets

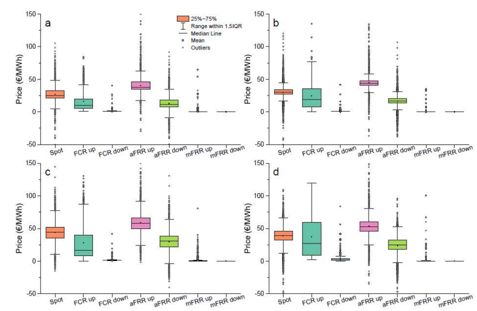


Participation in day-ahead, balancing and reserve markets

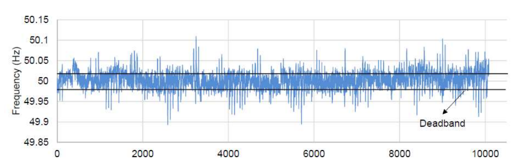


FCR frequency response properties

Abundant market data

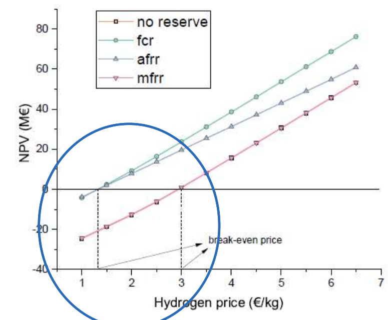


Historical Denmark market data

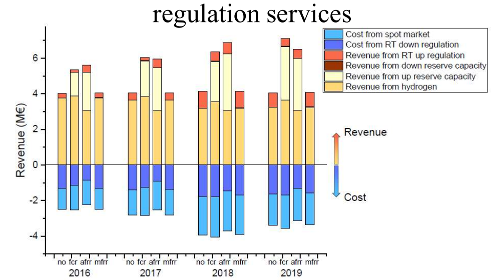


Historical frequency observation

Provision of frequency regulation services benefits economics



System NPV when providing frequency regulation services



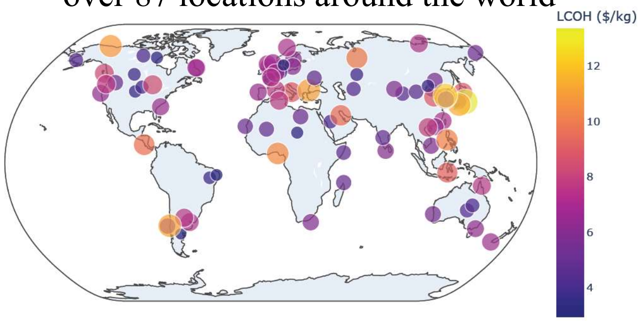
System operational cost breakdown

Economic evaluation based on advanced electrolysis models

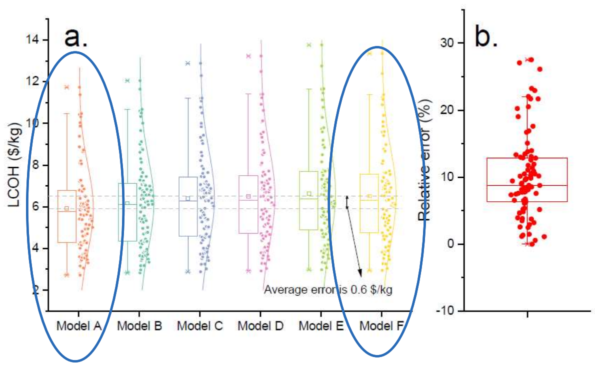
Key output 5: Granularity of electrolysis models matters when assessing green hydrogen economy

Examination of the LCOH (offgrid wind/electrolyser)

over 87 locations around the world

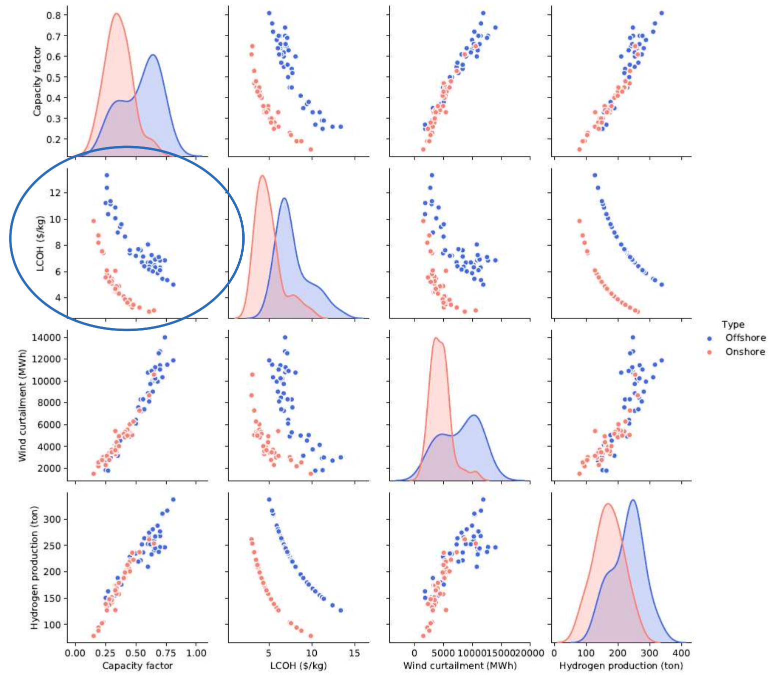


LCOH of the relevant locations



LCOH distribution given different models (eff., operation range, start-up time)

- **Over-simplistic model can lead to up to 25% errors**



Hydrogen production, wind curtailment, capacity factor and LCOH

- **Capacity factor significantly affects the LCOH**
- **Onshore applications outperform their offshore counterpart**

Concluding remarks

- Using models of electrolyser with dynamic properties in various calculation can offer some insight knowledge to technological performance and PtX economy.
- Intelligent operation strategies can effectively handle both uncertainties and flexibility, resulting reduction of variable operation cost, e.g. up to 24% for a wind/electrolyser system.
- A university-industry partnership is fantastic and mutually beneficial, particularly concerning emerging technologies & complex systems.
- Aware of the gap between research and real world challenges is important.
- Both parties are looking forward to implementing and testing of the developed solution.

Nice to read

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Journal articles

[1] Y. Zheng, S. You, H. W. Bindner, and M. Münster, “Optimal day-ahead dispatch of an alkaline electrolyser system concerning thermal–electric properties and state-transitional dynamics,” Applied Energy, vol. 307, p.118091, 2022.

[2] Y. Zheng, S. You, X. Li, H. W. Bindner, and M. Münster, “Data-driven robust optimization for optimal scheduling of power to methanol,” Energy Conversion and Management, vol. 256, p. 115338, 2022.

[3] Y. Zheng, S. You, H. W. Bindner, and M. Münster, “Incorporating optimal operation strategies into investment planning for wind/electrolyser system,” CSEE Journal of Power and Energy Systems, 2022.

[4] S. Klyapovskiy, Y. Zheng, S. You, and H. W. Bindner, “Optimal operation of the hydrogen-based energy management system with p2x demand response and ammonia plant,” Applied Energy, vol. 304, p. 117559, 2021.

[5] Y. Zheng., S. You, etc., “Data-driven method for optimal day-ahead operation of a wind/hydrogen system under mixed uncertainties”, Applied Energy, vol 329, p120201, 2023

[6] Y. Zheng. S. You, etc., Economic evaluation of a power-to-hydrogen system providing frequency regulation reserves: a case study of Denmark (International Journal of Hydrogen Energy ,accepted)

[7] Y. Zheng. S. You, etc., Model-based economic analysis of off-grid wind/hydrogen systems (Renewable and Sustainable energy Reviews , under review)

Conference

[1] Y. Zheng, S. You, J. Wang, X. Li, H. W. Bindner, and M. Münster, “Data-driven robust chance constrained optimization for optimal operation of a wind/hydrogen system,” in International Conference on Applied Energy 2021, 2021.

[2] S. Klyapovskiy, Y. Zheng, S. You, and H. W. Bindner, “Economy vs sustainability: comparison of the two operational schedules for the hydrogen-based energy management system with p2x demand response,” in ICAE2020: the 12th International Conference on Applied Energy. Elsevier, 2020.

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The transnational joint programming platform (JPP) ERA-Net SES unites 30 funding partners from European and associated countries. It functions as a network of owners and managers of national and regional public funding programs in the field of research, technical development and demonstration. It provides a sustainable and service-oriented joint programming platform to finance transnational RDD projects, developing technologies and solutions in thematic areas like smart power grids, integrated regional and local energy systems, heating and cooling networks, digital energy and smart services, etc.

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